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SPACE SHUTTLE PROPELLANT CONSTITUTIVE LAW VERIFICATION TESTS

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Final Technical Report
31 March 1995

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Control No. U-95-7007

SPACE SHUTTLE PROPELLANT CONSTITUTIVE LAW VERIFICATION TESTS

31 March 1995

Performed for
The National Aeronautics and Space Administration
Under Contract
NAS 8-39619 Mod. 3

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12a. DISTRIBUTION / AVAILABILITY STATEMENT

As part of the Propellants Task (Task 2.0) on the Solid Propulsion Integrity Program (SPIP), a database of material properties was generated for the Space Shuttle Redesigned Solid Rocket Motor (RSRM) PBAN-based propellant. A parallel effort on the Propellants Task was the generation of an improved constitutive theory for the PBAN propellant suitable for use in a finite element analysis (FEA) of the RSRM. The outcome of an analysis with the improved constitutive theory would be more reliable prediction of structural margins of safety.

The work described in this report was performed by Materials Laboratory personnel at Thiokol Corporation/Huntsville Division under NASA contract NAS8-39619, Mod.3. The report documents the test procedures for the refinement and verification tests for the improved Space Shuttle RSRM propellant material model, and summarizes the resulting test data. TP-H1148 propellant obtained from mix E660411 (manufactured February 1989) which had experienced ambient igloo storage in Huntsville, Alabama since January 1990, was used for these tests.

13. ABSTRACT

This document contains information which falls under the purview of the U.S. Munitions List, as defined in the International Traffic and Arms Regulations. It shall not be transferred to foreign nationals, in the U.S. or abroad, without specific approval. Penalty for violations is described in ITAR, Section 127. Distribution authorized to U.S. Government Agencies and U.S. Government Agency Contractors ONLY; Critical Technology, March 1995. Other requests for this document shall be referred to NASA/MSFC.ER41/Solid Propulsion Research and Technology Office, Huntsville, Alabama 35812.

1 INTRODUCTION

As part of the Propellants Task (Task 2.0) on the Solid Propulsion Integrity Program (SPIP), a database of material properties was generated for the Space Shuttle Redesigned Solid Rocket Motor (RSRM) PBAN-based propellant. A parallel effort on the Propellants Task was the generation of an improved constitutive theory for the PBAN propellant suitable for use in a finite element analysis (FEA) of the RSRM. The outcome of an analysis with the improved constitutive theory would be a more reliable prediction of structural margins of safety.

Dr. Stephen Peng, of the Jet Propulsion Laboratory, developed the first three-dimensional, nonlinear, viscoelastic constitutive law (JPL Model) for the RSRM PBAN propellant. However, Dr. Peng's original theory contained instabilities which prevented its successful FEA implementation. Dr. Charlie Springfield, of SVERDRUP Technologies, provided modifications to Dr. Peng's original theory (Sverdrup Model) which removed the instabilities, and permitted its first successful implementation in an FEA code (ABAQUS).

The constitutive theory developed by Dr. Peng was based on mechanical property data obtained from monotonic loading histories. Tests such as uniaxial tension-to-failure, and tensile stress relaxation tests (both small and finite strain) were performed to generate the required mechanical properties. In addition, biaxial tensile tests were performed to generate data for the multidimensional component of the theory, whereas volume dilatation measurements were made to generate the damage component of the material model.

For the FEA results to be valid, however, the improved constitutive theory would necessarily be required to predict structural responses to any arbitrary loading history. Unrealistic results were obtained from analyses performed with the baseline Sverdrup Model which indicated instabilities associated with a compressive stress state. Therefore, in an effort to refine the constitutive theory as modified by Dr. Springfield, uniaxial compression stress relaxation tests were performed. Further, to verify finite element analyses performed on the large cylindrical specimen, additional mechanical property tests were conducted with various propellant specimen geometries subjected to more complicated monotonic loading conditions for comparison.

The work described in this report was performed by Materials Laboratory personnel at the Huntsville Division under NASA contract NAS 8-39619, Mod. 3. The report documents the test procedures for the refinement and verification tests for the improved Space Shuttle RSRM propellant material model, and summarizes the resulting test data. TP-H1148 propellant obtained from mix E660411 (manufactured February 1989) which had experienced ambient igloo storage in Huntsville, Alabama since January 1990, was used for these tests.

This work was performed under Contract Number NAS 8-39619 with Thiokol Corporation as part of NASA's Solid Propulsion Integrity Program. This document contains information which falls under the purview of the U.S. Munitions List, as defined in the International Traffic and Arms Regulations. It shall not be transferred to foreign nationals, in the U.S. or abroad, without specific approval. Penalty for violations is described in ITAR, Section 127. Distribution authorized to U.S. Government Agencies and U.S. Government Agency Contractors ONLY; Critical Technology, March 1995. Other requests for this document shall be referred to NASA/MSFC, ER41/Solid Propulsion Research and Technology Office, Huntsville, Alabama 35812.

2 SPECIMEN PREPARATION

Two propellant blocks were prepared to provide two flat, parallel, bonding surfaces 5.5 inches apart on each block. Eight end-tabs were bonded to each bonding surface with a two-part epoxy adhesive. The propellant and end-tabs were inserted into a special bonding fixture which was manufactured to ensure corresponding centerlines for the end-tabs. After adhesive cure, each propellant block with bonded end-tabs was removed from the bonding fixture, and eight approximately equal propellant sections were knife-cut from the block with each section containing two end-tabs. Each propellant section was then machined to final configuration in a lathe. Two rotating chucks held each propellant section by the end-tabs in the lathe. This procedure ensured the coaxiality of the propellant centerline and the end-tab centerline. The two propellant blocks provided sufficient specimens for the all the tests described below.

3 COMPRESSIVE STRESS RELAXATION TESTS

As a result of unrealistic analytical predictions obtained with the baseline Sverdrup Model, compressive stress relaxation tests were performed to provide mechanical property data from which refinements could be made. These tests consisted of various levels of constant uniaxial compression applied to the large cylindrical specimens previously developed under SPIP[1]. Figure 1 illustrates the large cylindrical test specimen used. These tests measured the nonlinear viscoelastic response of the RSRM propellant in a compressive stress state.

3.1 Test Procedure

The compressive stress relaxation tests were performed in an MTS® Axial/Torsional servohydraulic test machine at an ambient laboratory temperature of 77 ±5°F. The relaxation experiments were conducted at levels of two percent, five percent, and ten percent compressive strain. Strain was applied to each specimen based on displacement between the end-tabs, an effective gage length of five inches, and a crosshead speed of twenty inches per minute. Although the MTS servohydraulic test machine is capable of test speeds much greater than twenty inches per minute, to be consistent with the tensile tests which were performed on an Instron test machine, the test speed was restricted to twenty inches per minute. A new specimen was used for each test.

To determine volume dilatation, diametric and axial displacement measurements were made of each specimen during the relaxation tests. The diametric measurements were made with a KEYENCE® visible laser micrometer. The micrometer had a 0.01350 to 2.36220 inch measurement range with a measurement accuracy of ±0.00012 inch, and a repeatability of ±0.00002 inch. Axial displacements were measured during each test with an axial extensometer manufactured by MTS.

[1] J. R. Thompson, Linear Viscoelastic Characterization of the Space Shuttle Redesigned Solid Rocket Motor Propellant, (Huntsville, AL: Thiokol Corporation, 1993), U-93-4455.

The extensometer had a gage length of 1.000 ±0.002 inch (therefore strain was measured directly) with a linearity of 0.3 percent of the calibrated full-scale range.

The specimens were secured between the load cell and crosshead, and any loads induced by securing the specimen were removed by movement of the crosshead. The laser micrometer was then situated such that the laser beam impinged the specimen at midlength. The axial extensometer was attached to the specimen such that it centered the midlength of the specimen, and did not interfere with the laser micrometer. The initial specimen diameter was subsequently measured and recorded. A compressive displacement was applied to the specimen to achieve the desired strain level. The resulting stress decay and geometric changes were monitored for a period of eleven minutes.

The analog signals from the load cell, crosshead linear variable displacement transducer (LVDT), laser micrometer, and axial extensometer were recorded during the relaxation tests with a PC-based data acquisition system. The analog signals from each output device were connected to a MetraByte® DAS16 data acquisition board via a terminal-block interface box. Once received by the DAS16, the analog signals were converted to their digital representations by a 12-bit A/D converter. The DAS16 therefore is able to resolve one part in 4096, or one part in ±2048, of the original analog signal. The digital data was then read directly into a Lotus 1-2-3® spreadsheet with Lotus Measure®, a 1-2-3 add-in data acquisition program.

Because the greatest rate of change in stress, and specimen dimensions, occur immediately after application of the step strain in a relaxation experiment, a large sampling rate would be required to monitor the rapid changes of the propellant. However, the propellant response will substantially decrease a few seconds after strain application. As the duration of these tests was eleven minutes, and due to memory constraints associated with the PC-based data acquisition system, the large sampling rate could not be sustained throughout the entirety of each test.

Measure provides three data acquisition "stages" where different data acquisition parameters, including sampling rate and sampling duration, may be prescribed. Separate sampling rates and durations were chosen for each data acquisition stage. The first stage had a sampling rate of 1000 samples per minute with a duration of one minute. The second data acquisition stage had a sampling rate of 100 samples per minute for duration of one minute. The third data acquisition stage was prescribed with a sampling rate of ten samples per minute for the remaining nine minutes of the test.

3.2 Test Results

Figures 2 through 9 illustrate the test results obtained from the compressive stress relaxation tests performed on TP-H1148 propellant from mix E660411. Table I provides pertinent information for each specimen.

Figures 2 and 3 show the test results for specimens 1 and 2, respectively, when subjected to two percent compressive strain. These figures indicate excellent reproducibility for axial strain application at "small" strains, however, some variability in radial strain measurement is indicated. This variation in radial strain is more than likely attributable to laser micrometer placement in relation to the specimen; i.e. the laser beam not placed exactly in the same location on each specimen. Also, some variation in measured load is evident in these figures. This variation, however, appears to be within normal limits. A -10 pounds average load was indicated for the two specimens after eleven minutes.

Figures 4, 5, and 6 show the test results for specimens 1, 2, and 3, respectively, when subjected to five percent compressive strain. These figures indicate quite a large variation in load and axial displacement, as well as radial displacement, for the three specimens.

The Contracting Office Technical Representative (COTR) recommended that only two specimens be tested at each test condition in order to conserve propellant. However, a third specimen was needed at this test condition in an effort to reduce the variation in test data. As is evident, the additional test data failed to support a conclusion as to the true response of the propellant at this test condition. Subsequently, an average load measured after eleven minutes of approximately -51 pounds was indicated for all three specimens.

Figures 7, 8, and 9 illustrate the test data obtained for specimens 1, 2, and 3, respectively, when subjected to ten percent compressive strain. These figures indicate excellent reproducibility in axial strain application, and radial displacement measurement. Measured load appears to have variability with normal limits. An average load measured after eleven minutes was approximately -165 pounds for all three specimens.

4 COMBINED TENSION/TORSION TESTS

For the Space Shuttle RSRM propellant constitutive law verification tests, two types of combined loading histories were applied to the large cylindrical specimen shown in Figure 1. The first test was a stress relaxation test under combined tension/torsion, while the second test was a constant rate to failure for simultaneous tension and torsion at two test speeds. This is the first time data of this type has been obtained for the RSRM propellant.

4.1 Stress Relaxation

These tests measured the viscoelastic response of the RSRM propellant when subjected to a complex load. Tensile and torsional displacements were simultaneously applied to each specimen, and the propellant's response was measured.

4.1.1 Test Procedure

The tension/torsion stress relaxation tests were performed with the MTS servohydraulic tester at an ambient laboratory temperature of 77°F. The test specimens were secured between the load cell and the crosshead, and any load induced by this process was removed by relocating the crosshead. The original specimen diameter was then measured and recorded.

A fifteen percent axial strain, and thirty percent torsional strain were simultaneously applied to each specimen. The axial strain was applied at a test speed of twenty inches per minute, while the rotational strain was applied at 48.9 radians per minute. The rotational speed was chosen so that the axial and torsional strain levels would be attained at the same time. These strain levels were chosen based on previous work on SPIP (see Reference 1) where the tensile and shear stress relaxation was measured separately. The chosen strain levels represent the maximum strain levels applied in the previous study.

The load cell, crosshead LVDT, crosshead rotational variable displacement transducer (RVDT), and laser micrometer signals were monitored for a period of eleven minutes. The signals were acquired and recorded with the data acquisition system described in Section 3.1.

4.1.2 Test Results

Figures10 and 11 illustrate the viscoelastic response of the RSRM propellant when subjected to a simultaneous tension/torsion stress state. These figures show the propellant's response for load, torque, and measured radial displacement. They do not indicate measured axial displacement. Due to the nature of the test, it was impractical to attach an axial extensometer to measure axial strain. Also, the figures indicate that maximum rotation was achieved just prior to maximum axial displacement.

These figures indicate excellent reproducibility for all measured material responses, and that the relaxation rate is essentially the same for load and torque. This indicates that the same relaxation function can be used when describing tensile, shear, and bulk modulus.

An average load of approximately 100 pounds was measured after eleven minutes. An average torque of approximately 40 inch-pounds was indicated after eleven minutes. An average radial displacement of approximately -0.09 inch was measured after eleven minutes.

4.2 Constant Rate to Failure Tests

These tests measured the nonlinear, and failure responses of the RSRM propellant when subjected to a complex monotonic stress history.. A combined stress state of tension and torsion was simultaneously induced in the propellant at a constant test speed.

4.2.1 Test Procedure

These tests were conducted with the MTS servohydraulic tester at an ambient laboratory temperature of 77°F. The test specimens were secured between the load cell and the crosshead, and any load induced by this process was removed by relocating the crosshead. The original specimen diameter was then measured and recorded.

Two test speeds were used in these tests to indicate the rate dependence of the failure properties for the RSRM propellant. For the first set of tests, axial strain was applied at a test speed of 0.2 inch per minute, while the rotational strain was applied at 0.489 radians per minute. For the second set of tests, the axial test speed was two inches per minute with a rotation rate of 4.89 radians per minute. The axial and rotational test speeds were selected as decades of the rates used in the stress relaxation tests.

The load cell, crosshead LVDT and RVDT, and the laser micrometer signals were monitored until specimen failure. The signals were acquired and recorded with the data acquisition system described in Section 3.1.

4.2.2 Test Results

Figures 12 and 13 show the test results obtained for the constant rate to failure tests conducted at an axial test speed of 0.2 inch per minute. These figures indicate excellent reproducibility in both viscoelastic, and failure responses. Specimen 1 indicates failure after approximately 5.5 minutes, while specimen 2 indicates failure at approximately 5.3 minutes. Otherwise, the responses of the two specimens are virtually identical.

As is evident from these figures, the selected rotation rate was too fast to permit torque to be applied until failure. This is due to limitations in equipment as the MTS tester does not permit a constantly rotating crosshead.

The load and torque responses are interesting in the fact that once the maximum rotation is achieved at approximately 3.5 minutes, the load begins to increase consistent with a simple uniaxial tensile test, while the torque indicates behavior consistent with a shear stress relaxation test. Further, even after achieving maximum rotation, the radial displacement continues to decrease in a uniformly monotonic fashion until specimen failure.

These figures indicate that the simultaneous application of torsion reduces the propellant's tensile stress capability, but when the shear stress is allowed to relax, the propellant recovers some of its tensile stress capability.

The average failure load for these specimens was an approximately 260 pounds. The average failure torque was approximately 40 inch-pounds. The average change in specimen diameter at failure was approximately -0.09 inch.

Figures 14 and 15 illustrate the response of the RSRM propellant when tested at an axial test speed of two inches per minute. The general response of the propellant subjected to these test conditions was similar to that observed in the 0.2 inch per minute tests. However, the average failure load increased to approximately 300 pounds, and the change in specimen diameter increased to an average of approximately -0.05 inch at failure. Propellant failure occurred at an average test time of approximately 0.7 minutes for these specimens.

Interestingly, the average failure torque remained constant at forty inch-pounds for the two test conditions. It is evident from a comparison of Figures 12 through 15 that this is due to the difference in propellant relaxation rate.

5 CANTILEVER BEAM TESTS

These tests were conducted to verify the prediction of the RSRM material model conducted on a specimen geometry with specific boundary conditions which has a known analytical solution. The cantilever beam test conducted during this study was a creep test where a specimen of uniform square cross section, and finite length, was loaded only by its weight.

5.1 Test Procedure

Propellant specimens were guillotine-cut from prepared blocks to have nominal dimensions of 0.5 inch x 0.5 inch x 6.0 inches long. The specimens were then knife-cut provide three specimens each with lengths 1.875 inches, 3.25 inches, and 6.0 inches. The weight and dimensions of each specimen was measured and recorded. Table II provides the pertinent specimen information.

The propellant specimens were placed in the test fixtures as shown in Figure 16 with one specimen of each length per test fixture. The specimens were situated in the fixtures such that 0.5 inch of one end was clamped. This provided three specimens each with beam lengths of 1.375 inches, 2.75 inches, and 5.5 inches. A box of sufficient dimension was place under the specimens in each test fixture to prevent beam bending during test setup. A paper grid with a mesh of 10 x 10 per inch was placed behind each test fixture.

Once the propellant specimens were clamped in the test fixtures, the boxes in each test fixture were removed simultaneously to start the test. Photographs were taken at varying time intervals to record the deflection of each specimen. Deflections were determined from the photographs by measuring the distance from a reference line on the grid to the top of each propellant specimen.

5.2 Test Results

Only the specimens with a beam length of 5.5 inches provided measurable deflections during these tests. As a result, only data from these specimens are presented.

Figure 17 and Table III show the end deflection history for the three specimens with a beam length of 5.5 inches. Very reproducible test results were obtained. As seen in the figure, the average maximum end deflection of 1.51 inches was measured at thirty days. This figure indicates that equilibrium has not be attained at a time of thirty days.

Figure 18 and Table IV provide the deflection profile of the 5.5 inch specimens as a function of distance from the clamp (position along the beam). This figure shows excellent reproducibility for the specimens at these test conditions, and also indicates the time dependency of the creep compliance.

6 CONCLUSIONS

Excellent reproducibility was indicated for the material responses measured during the mechanical property tests performed for this study. The combined tension/torsion tests conducted in this study represent the first time material responses have been measured under complex stress states for the RSRM propellant.

Table I. Specimen Dimensions for Compressive Stress Relaxation Tests

Strain Level (inch/inch)	Specimen Number	Unstrained Diameter (inch)
-0.02	1	1.80720
	2	1.80699
	Average	1.80710
-0.05	1	1.80848
	2	1.82075
	3	1.80551
	Average	1.81158
-0.10	1	1.80705
	2	1.80822
	3	1.80711
	Average	1.80746

Table II. Specimen Dimensions for Cantilever Beam Tests, 5.5 inch Specimen

Specimen Number	Weight (gram)	H (inch)	A (inch)	B (inch)
1	47.47	0.512	0.535	0.535
2	47.29	0.510	0.528	0.528
3	47.81	0.517	0.532	0.532
Average	47.52	0.513	0.532	0.532

Table III. Cantilever Beam Test, End Deflection History for TP-H1148 Propellant
Beam Length = 5.5 inches

Time (minutes)	End Deflection, inch		
	Specimen 1	Specimen 2	Specimen 3
0	0.00	0.00	0.00
0.17	0.55	0.55	0.55
0.33	0.58	0.58	0.58
0.5	0.64	0.60	0.64
0.75	0.65	0.63	0.65
1	0.65	0.65	0.65
2	0.70	0.70	0.70
3	0.74	0.70	0.74
4	0.74	0.73	0.74
5	0.75	0.75	0.75
10	0.80	0.79	0.78
20	0.84	0.82	0.84
30	0.85	0.85	0.85
60	0.90	0.90	0.90
120	0.94	0.90	0.90
240	0.96	0.97	0.95
360	1.00	1.00	0.99
1,440	1.14	1.10	1.11
2,880	1.20	1.20	1.16
10,080	1.34	1.30	1.30
17,280	1.44	1.40	1.40
30,240	1.46	1.45	1.45
40,320	1.52	1.51	1.50

Table IV. Cantilever Beam Test, Deflection Profile for TP-H1148 Propellant
Beam Length = 5.5 inches

Distance from Clamp (inch)	Deflection Profile, inch											
	Time = 0.1667 min.			Time = 60 min.			Time = 17,280 min.			Time = 40,320 min.		
	#1	#2	#3	#1	#2	#3	#1	#2	#3	#1	#2	#3
0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.0	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.05	0.05	0.05	0.06	0.05
1.5	0.04	0.05	0.05	0.05	0.05	0.04	0.10	0.09	0.09	0.10	0.10	0.10
2.0	0.07	0.08	0.07	0.13	0.12	0.12	0.23	0.24	0.25	0.22	0.24	0.25
2.5	0.12	0.13	0.12	0.25	0.25	0.24	0.35	0.33	0.32	0.45	0.42	0.42
3.0	0.20	0.21	0.19	0.35	0.34	0.34	0.55	0.55	0.53	0.61	0.58	0.60
3.5	0.26	0.28	0.25	0.47	0.45	0.45	0.75	0.72	0.70	0.83	0.81	0.85
4.0	0.35	0.35	0.33	0.55	0.55	0.53	0.90	0.90	0.90	1.00	1.01	1.00
4.5	0.45	0.44	0.42	0.70	0.70	0.69	1.10	1.08	1.05	1.20	1.22	1.20
5.0	0.51	0.50	0.49	0.85	0.84	0.83	1.25	1.25	1.21	1.40	1.39	1.38
5.5	0.55	0.55	0.55	0.90	0.90	0.90	1.44	1.40	1.40	1.52	1.51	1.50

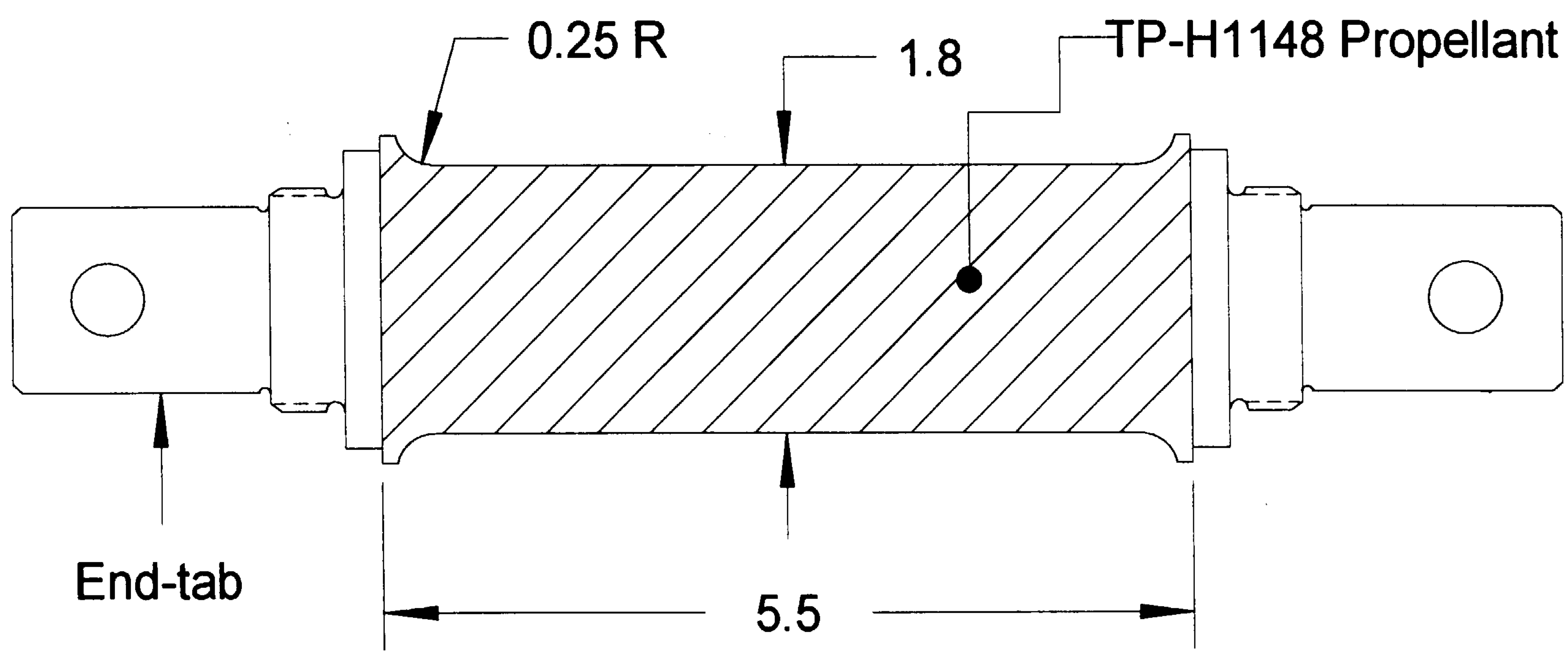

Figure 1. Cylindrical Test Specimen

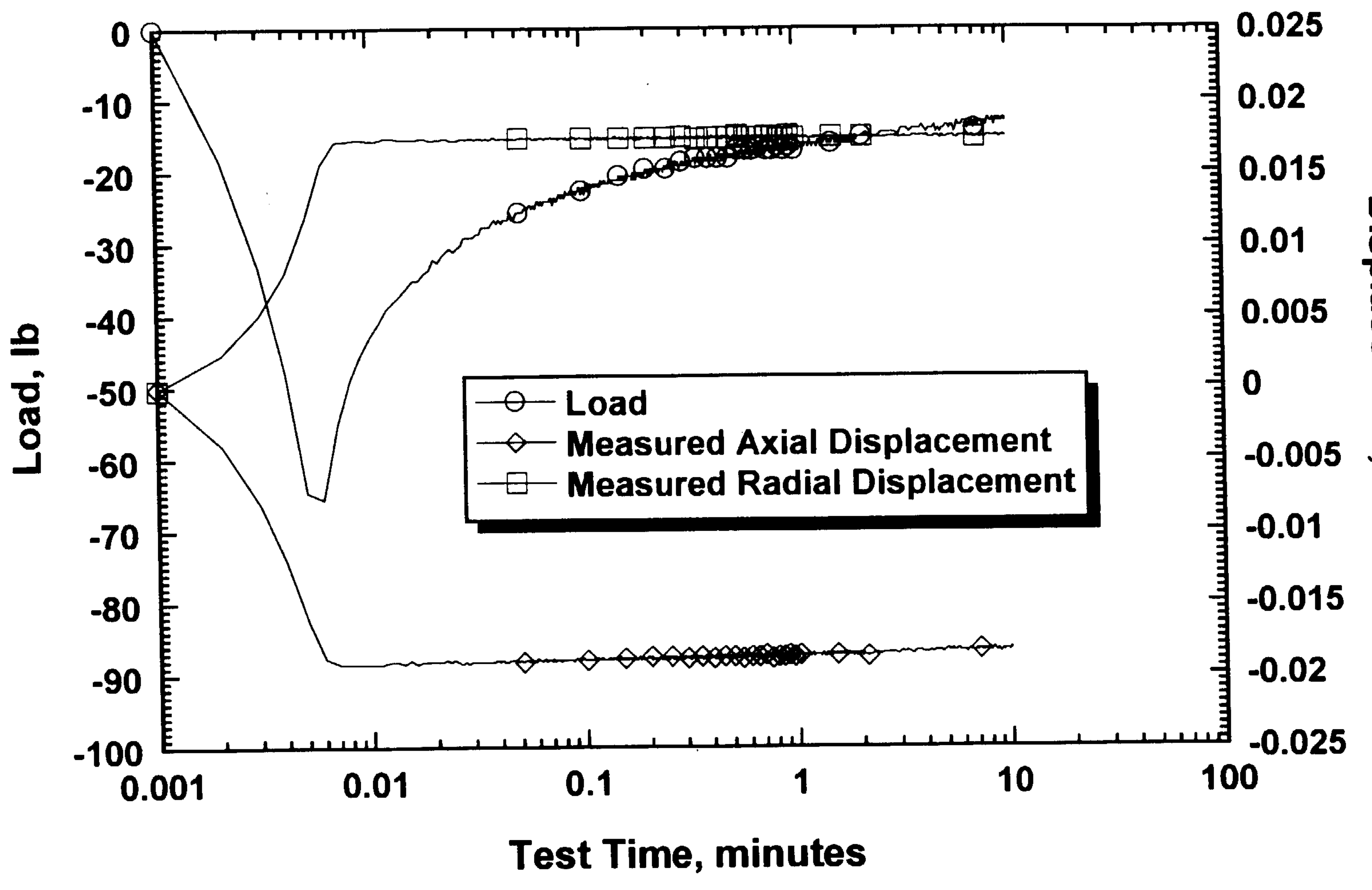

Figure 2. TP-H1148 Propellant Specimen 1 at Two Percent Compressive Strain

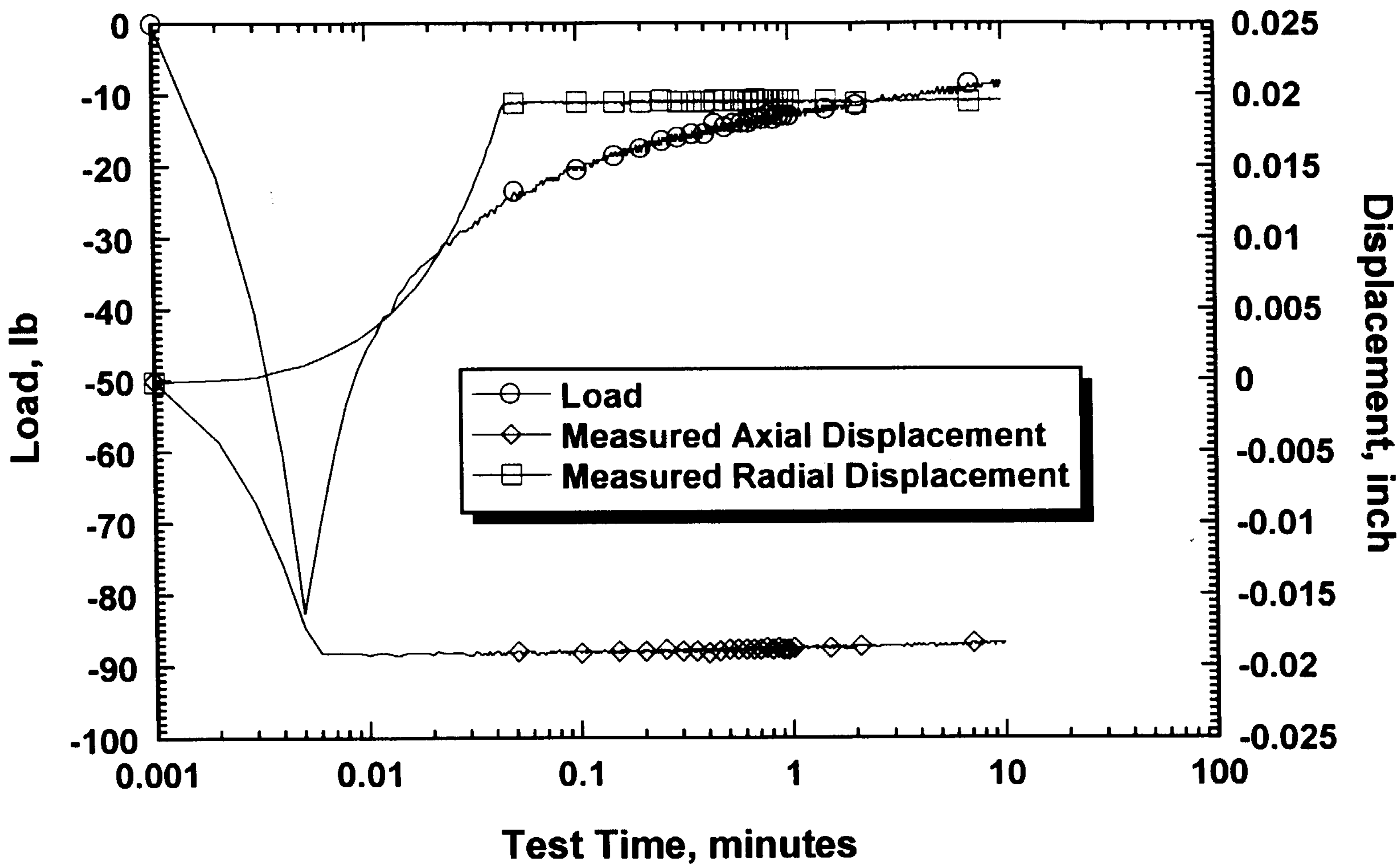

Figure 3. TP-H1148 Propellant Specimen 2 at Two Percent Compressive Strain

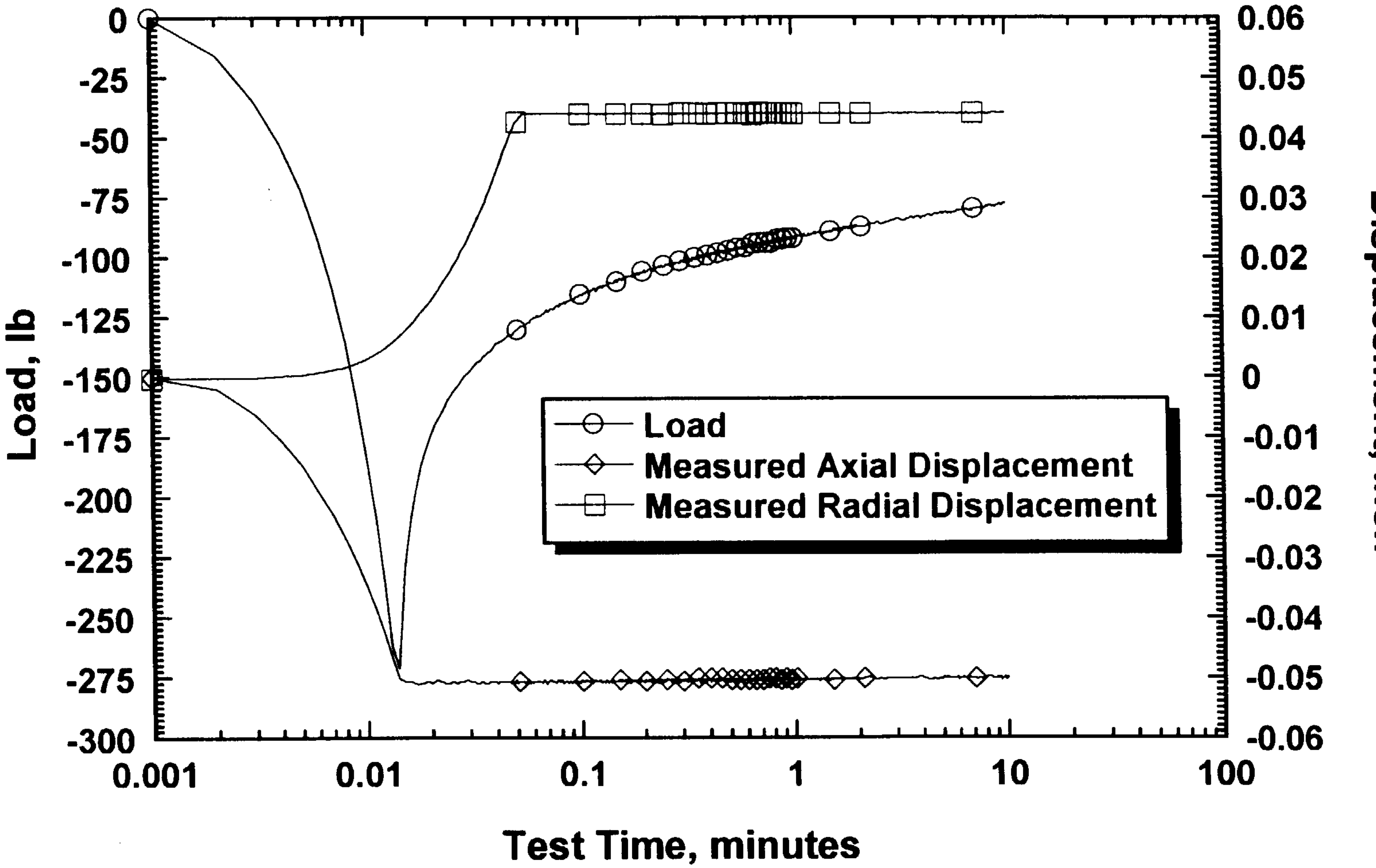

Figure 4. TP-H1148 Propellant Specimen 1 at Five Percent Compressive Strain

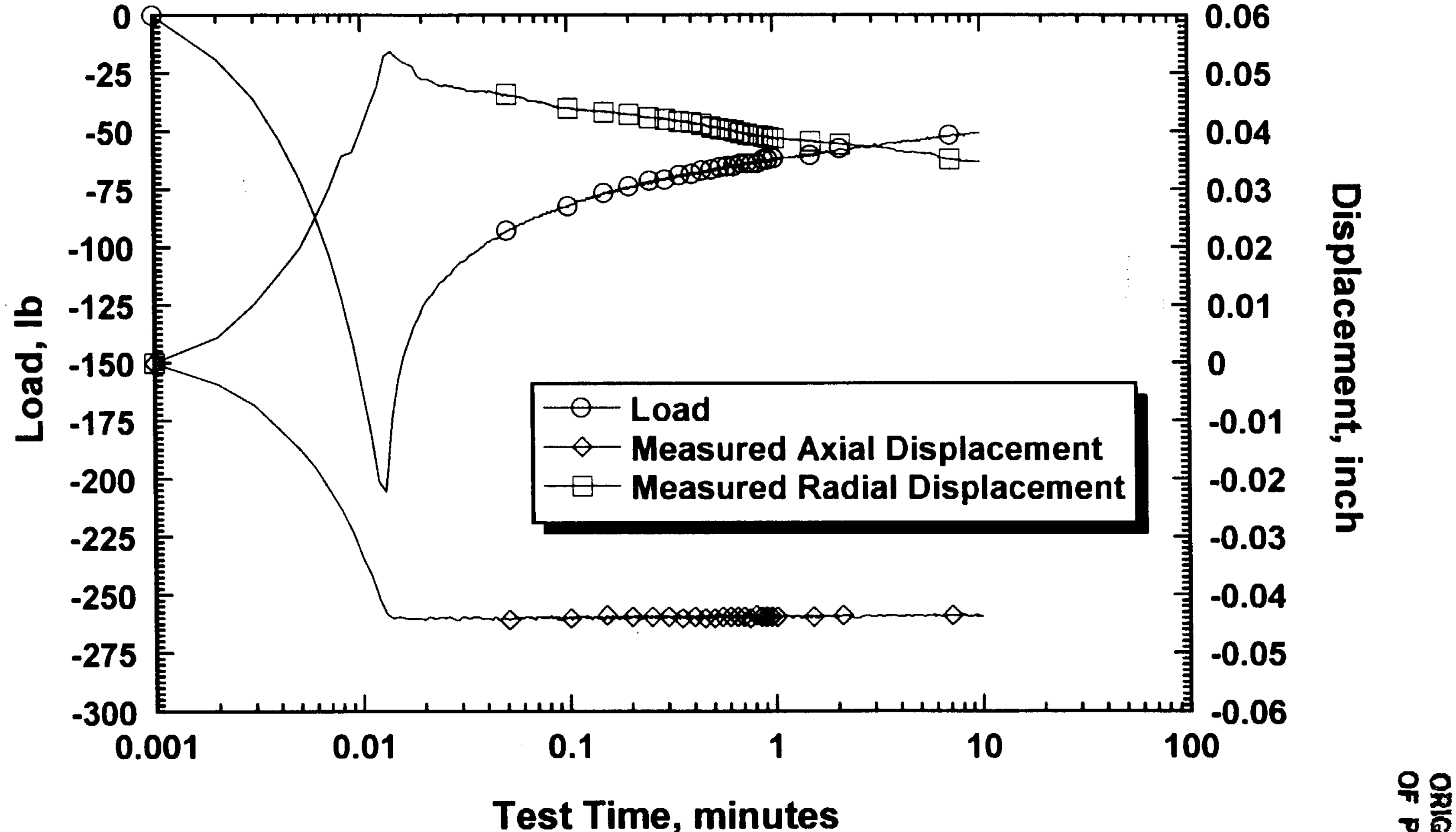

Figure 5. TP-H1148 Propellant Specimen 2 at Five Percent Compressive Strain

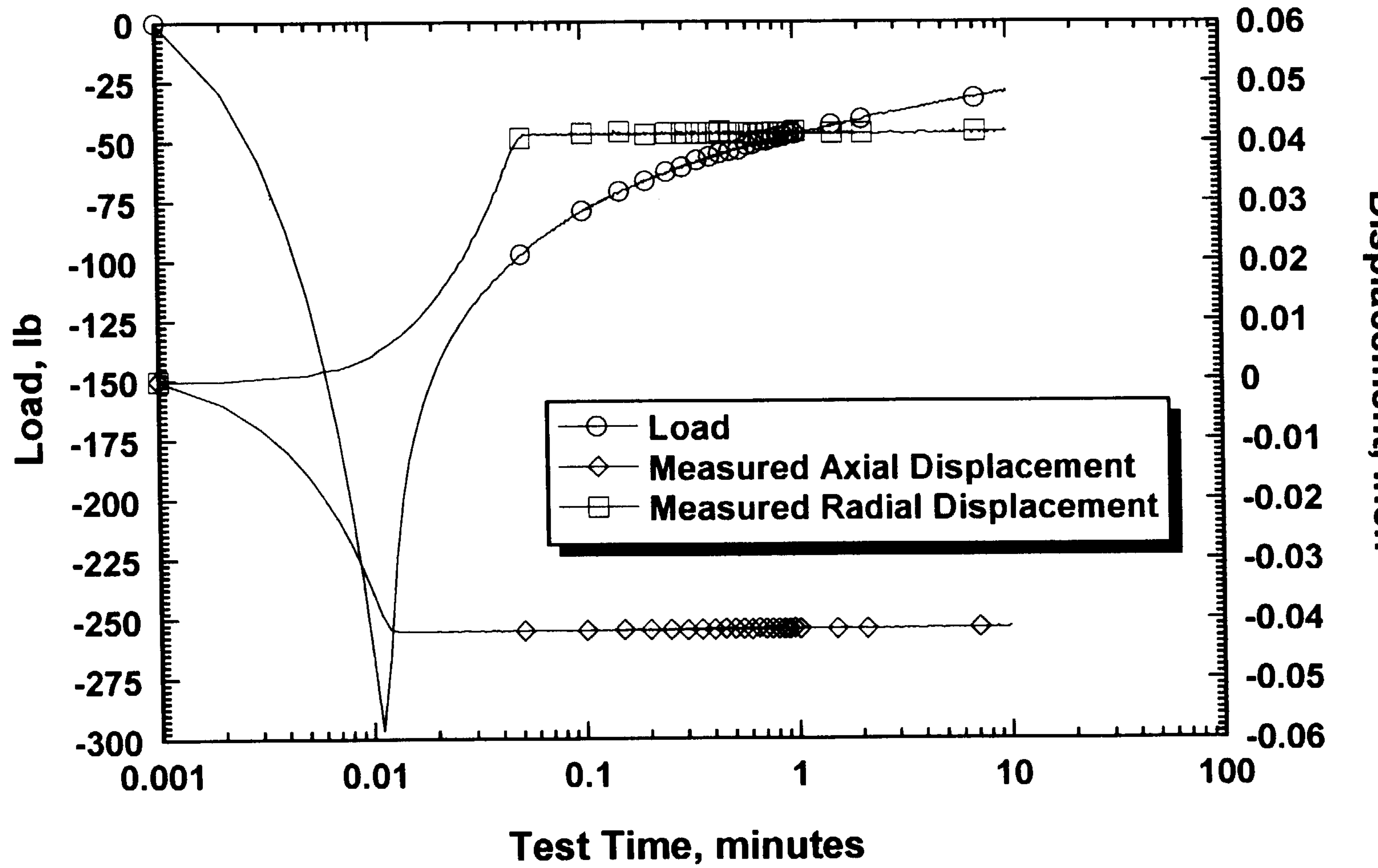

Figure 6. TP-H1148 Propellant Specimen 3 at Five Percent Compressive Strain

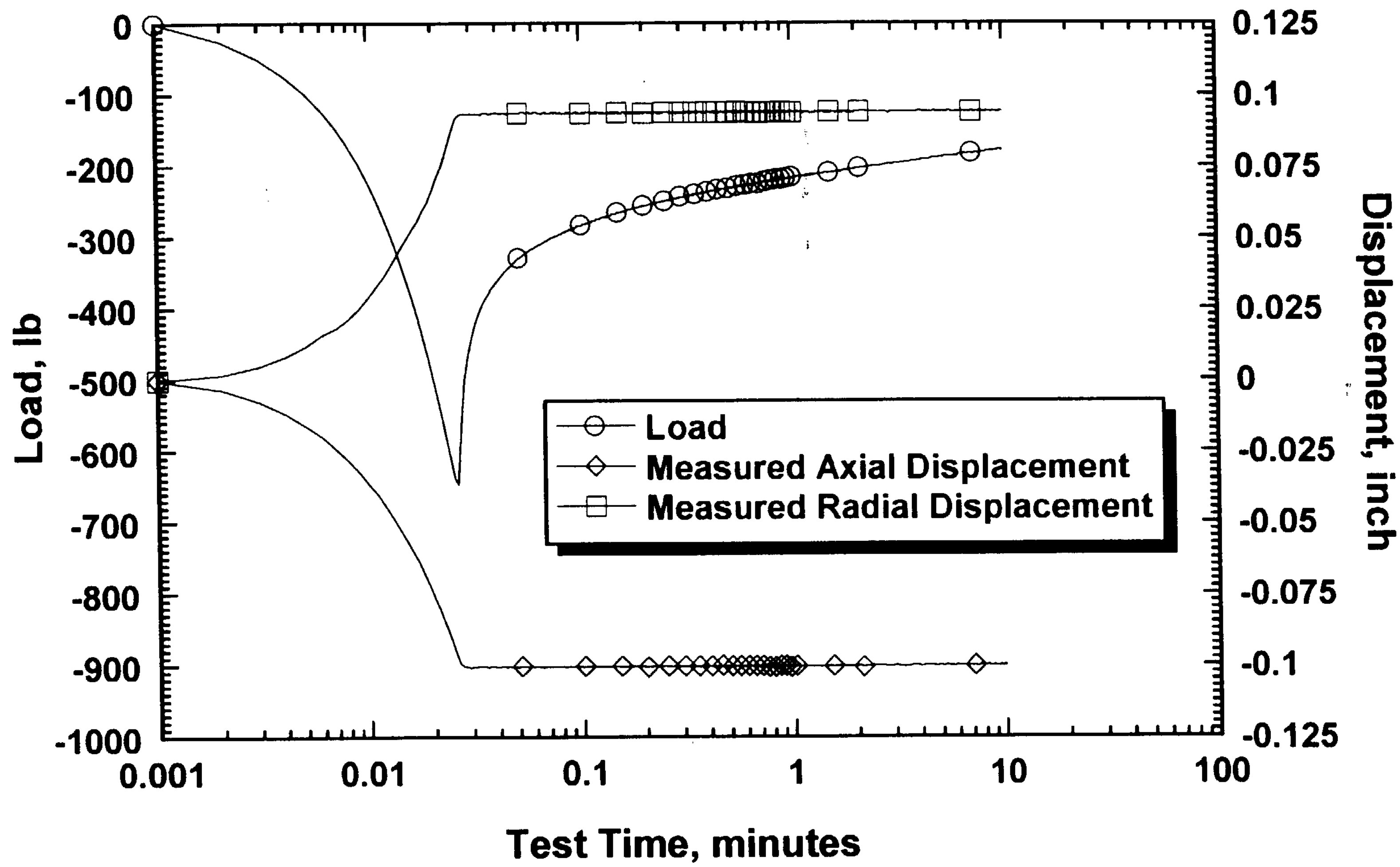

Figure 7. TP-H1148 Propellant Specimen 1 at Ten Percent Compressive Strain

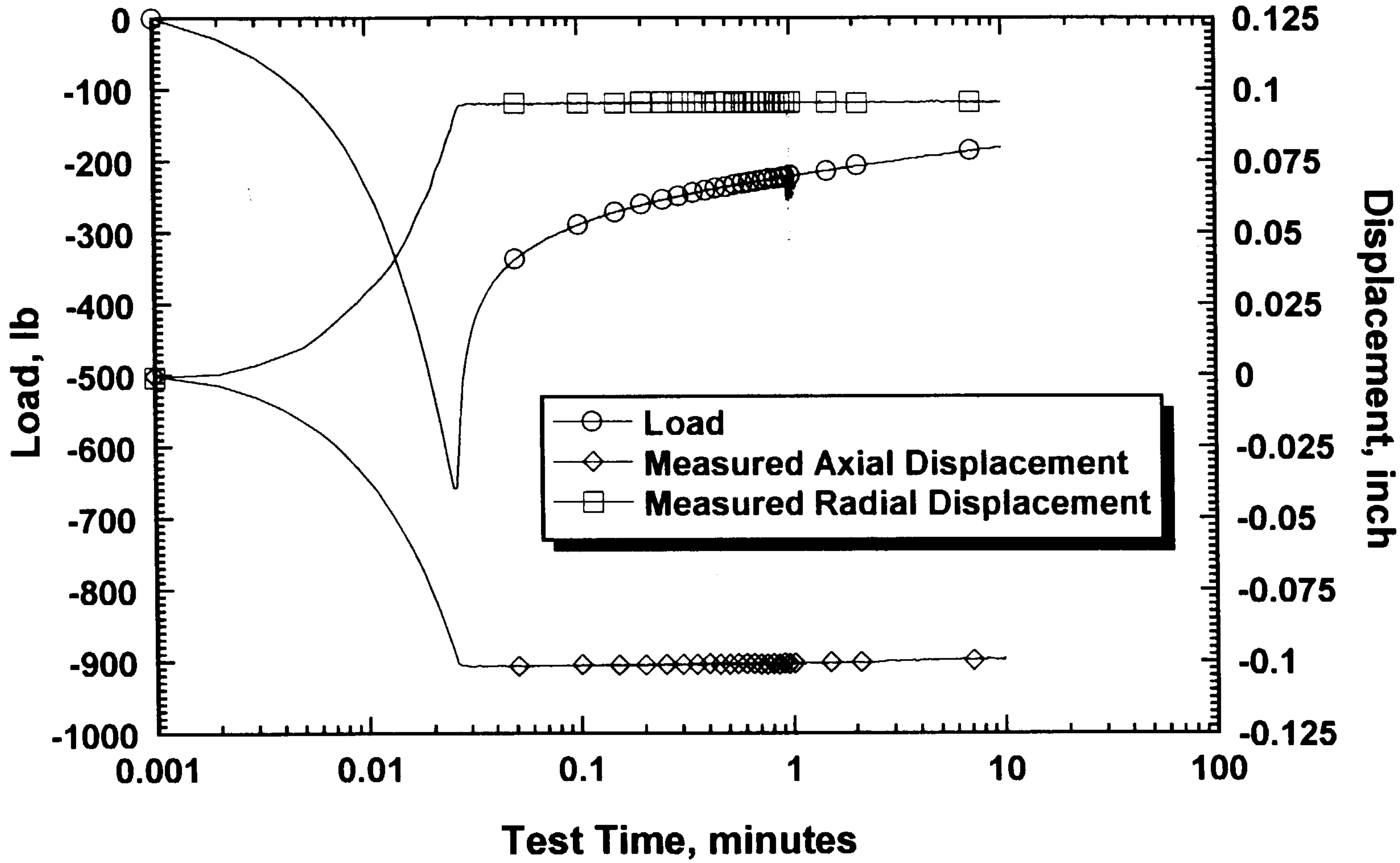

Figure 8. TP-H1148 Propellant Specimen 2 at Ten Percent Compressive Strain

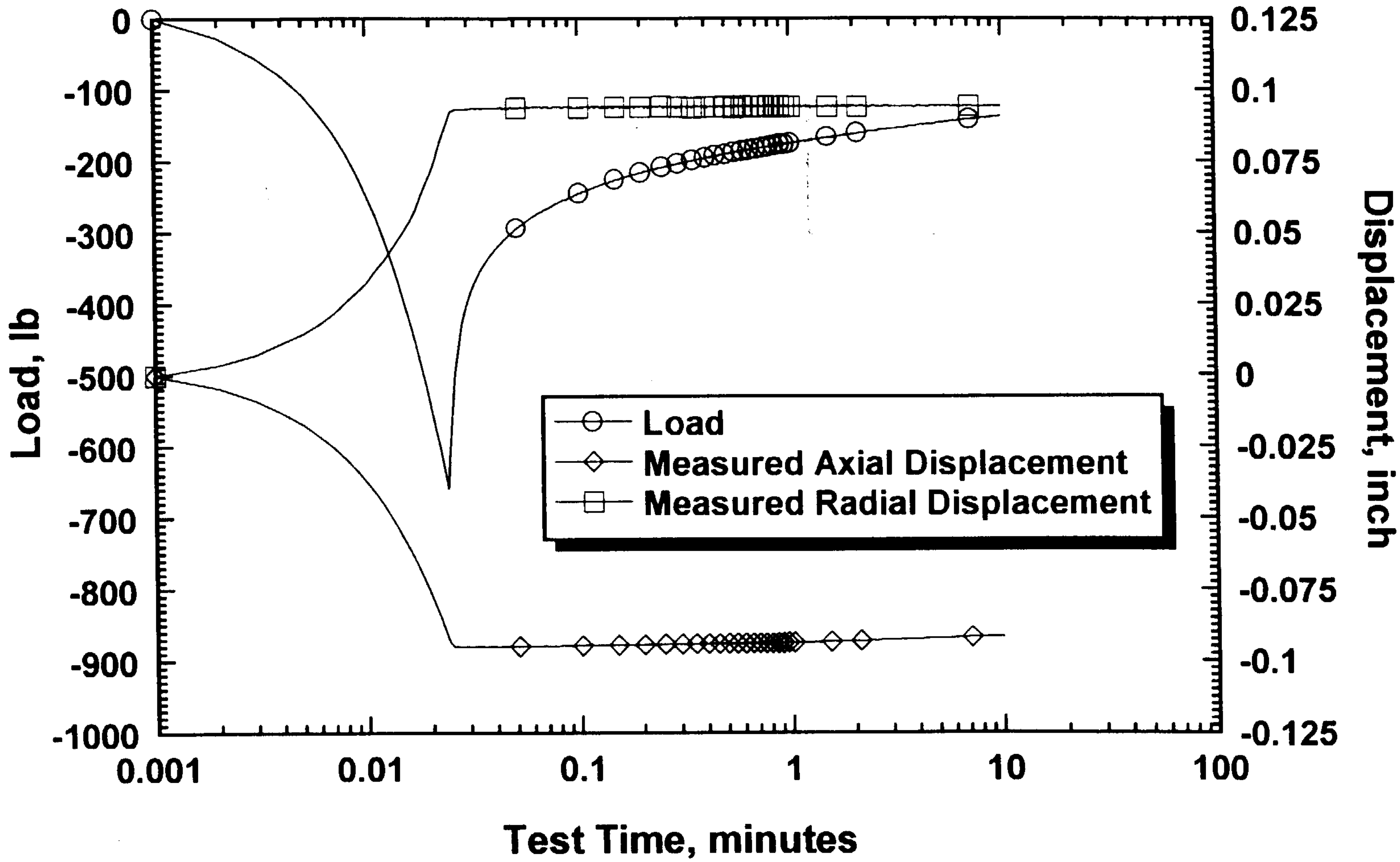

Figure 9. TP-H1148 Propellant Specimen 3 at Ten Percent Compressive Strain

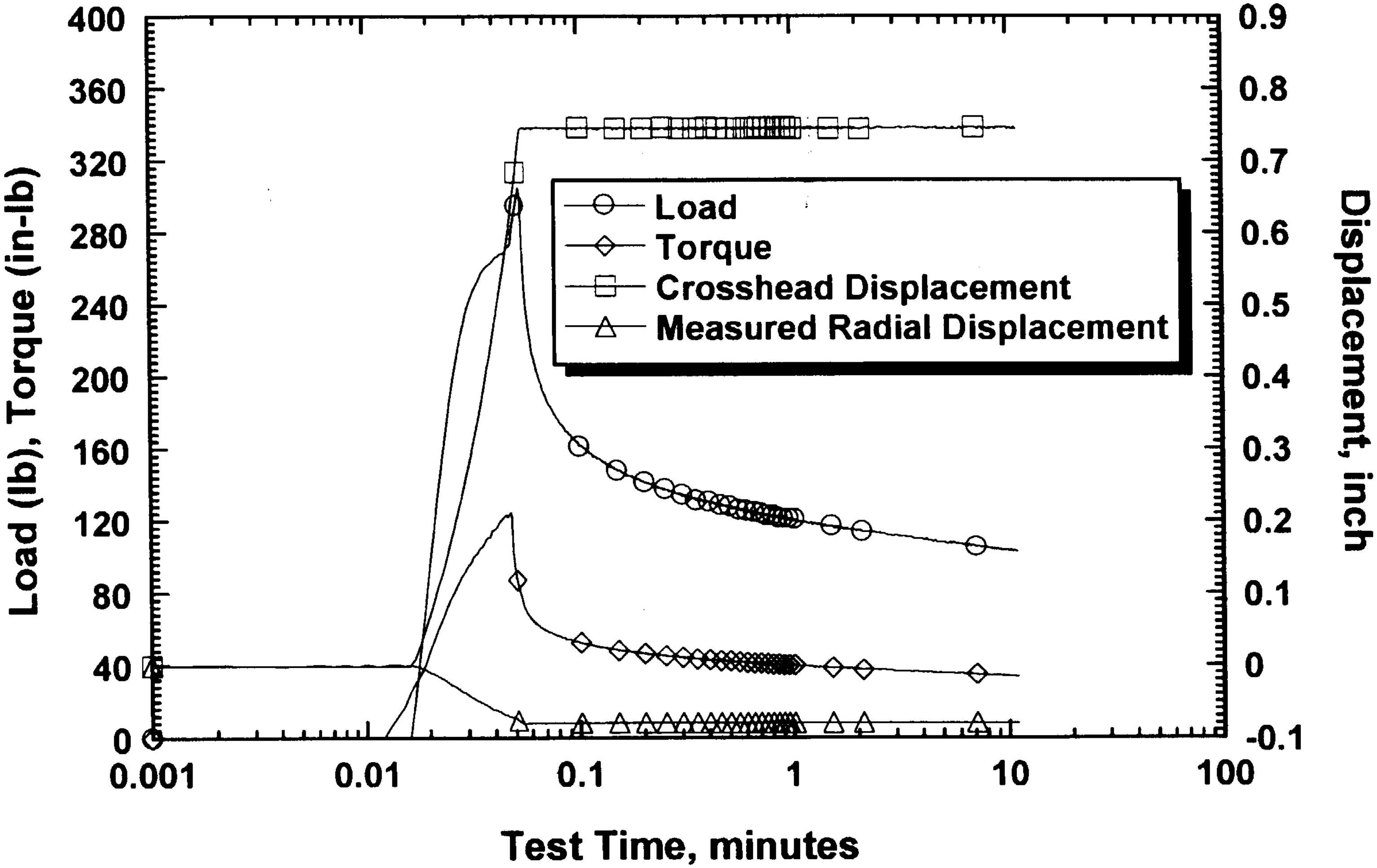

Figure 10. TP-H1148 Propellant Specimen 1 at Fifteen Percent Axial Strain and Thirty Percent Torsional Strain

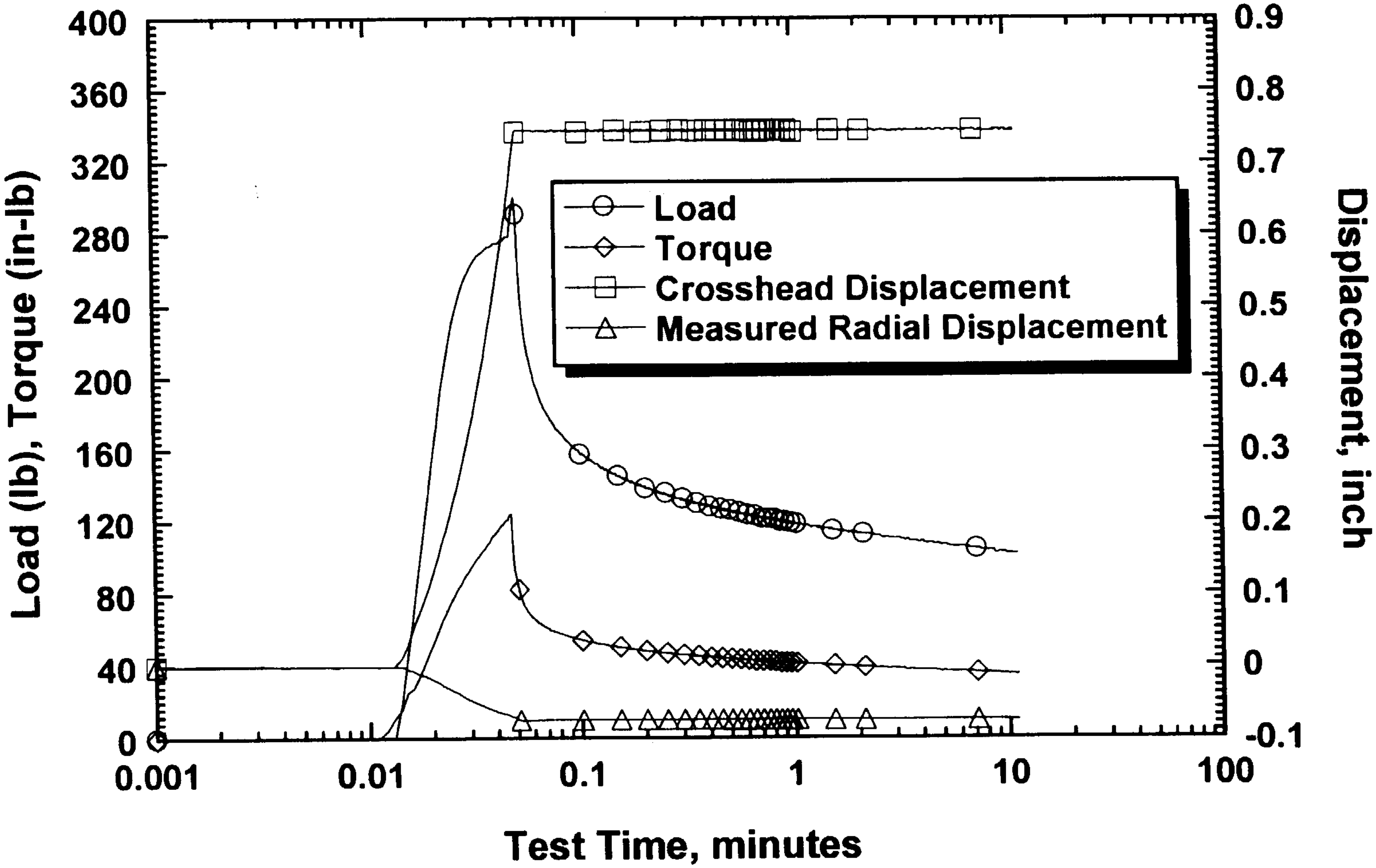

Figure 11. TP-H1148 Propellant Specimen 2 at Fifteen Percent Axial Strain and Thirty Percent Torsional Strain

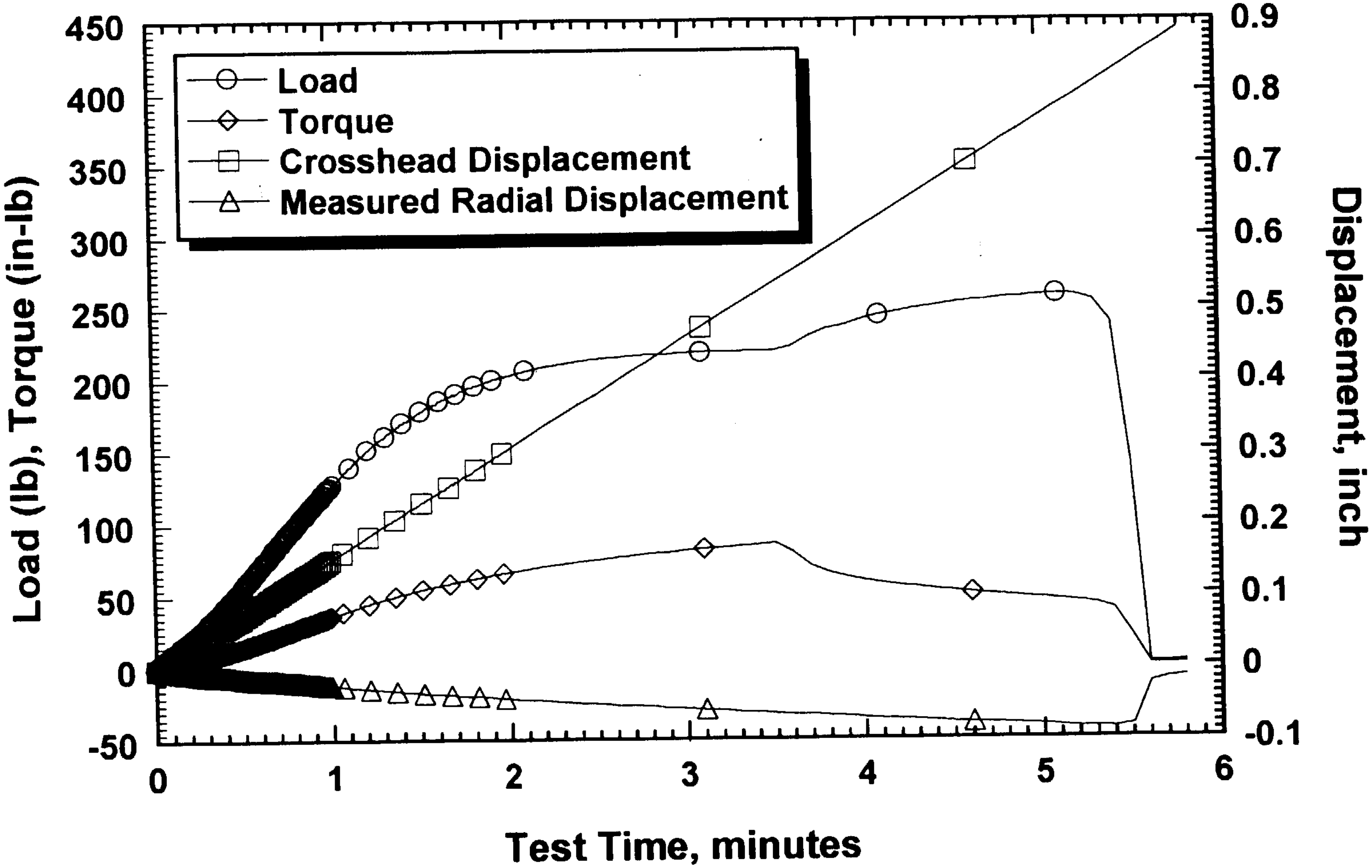

Figure 12. TP-H1148 Propellant Specimen 1 Under Simultaneous Tension/Torsion, Axial Test Speed of 0.2 inch per minute

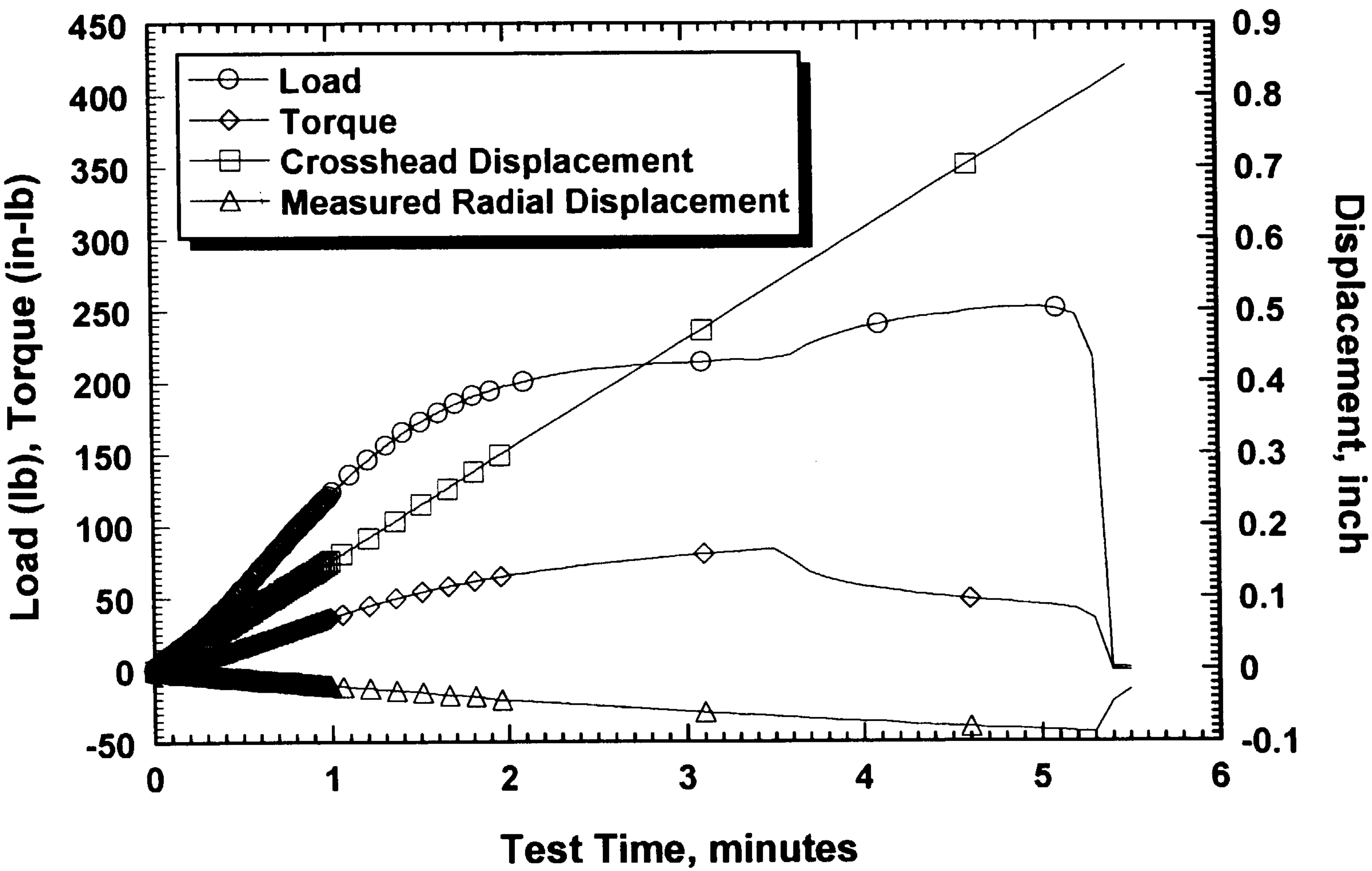

Figure 13. TP-H1148 Propellant Specimen 2 Under Simultaneous Tension/Torsion, Axial Test Speed of 0.2 inch per minute

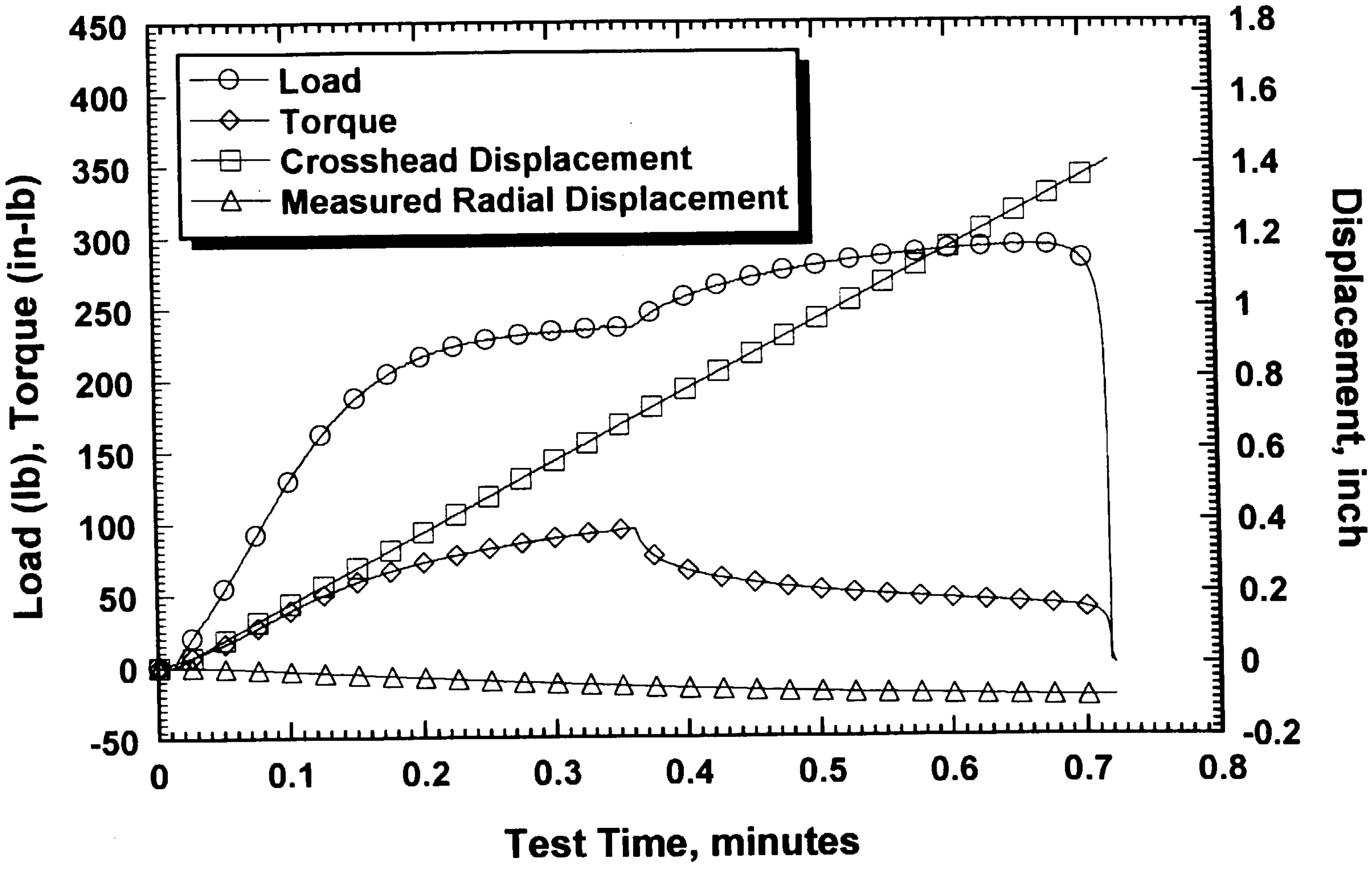

Figure 14. TP-H1148 Propellant Specimen 1 Under Simultaneous Tension/Torsion, Axial Test Speed of 2.0 inches per minute

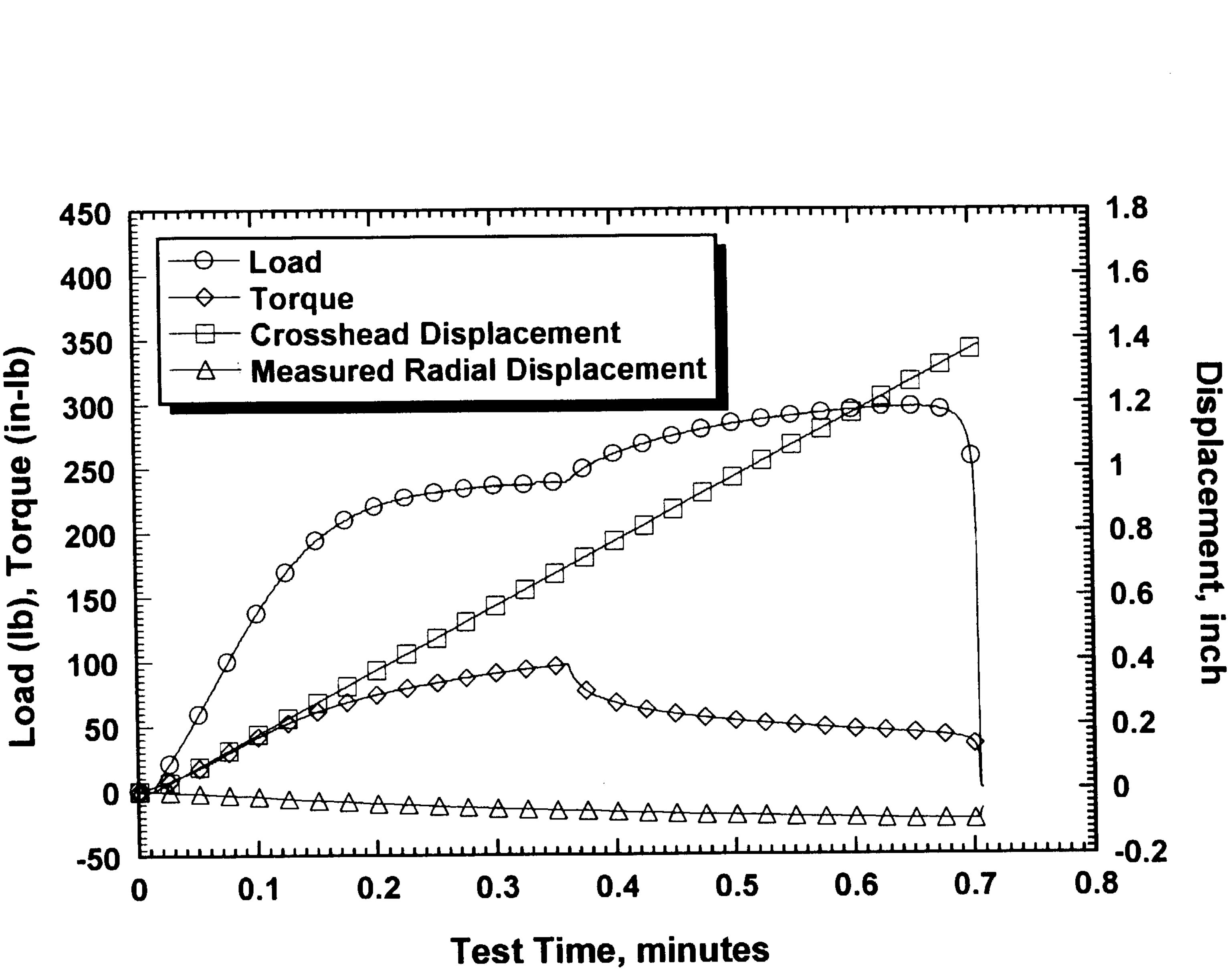

Figure 15. TP-H1148 Propellant Specimen 2 Under Simultaneous Tension/Torsion, Axial Test Speed of 2.0 inches per minute

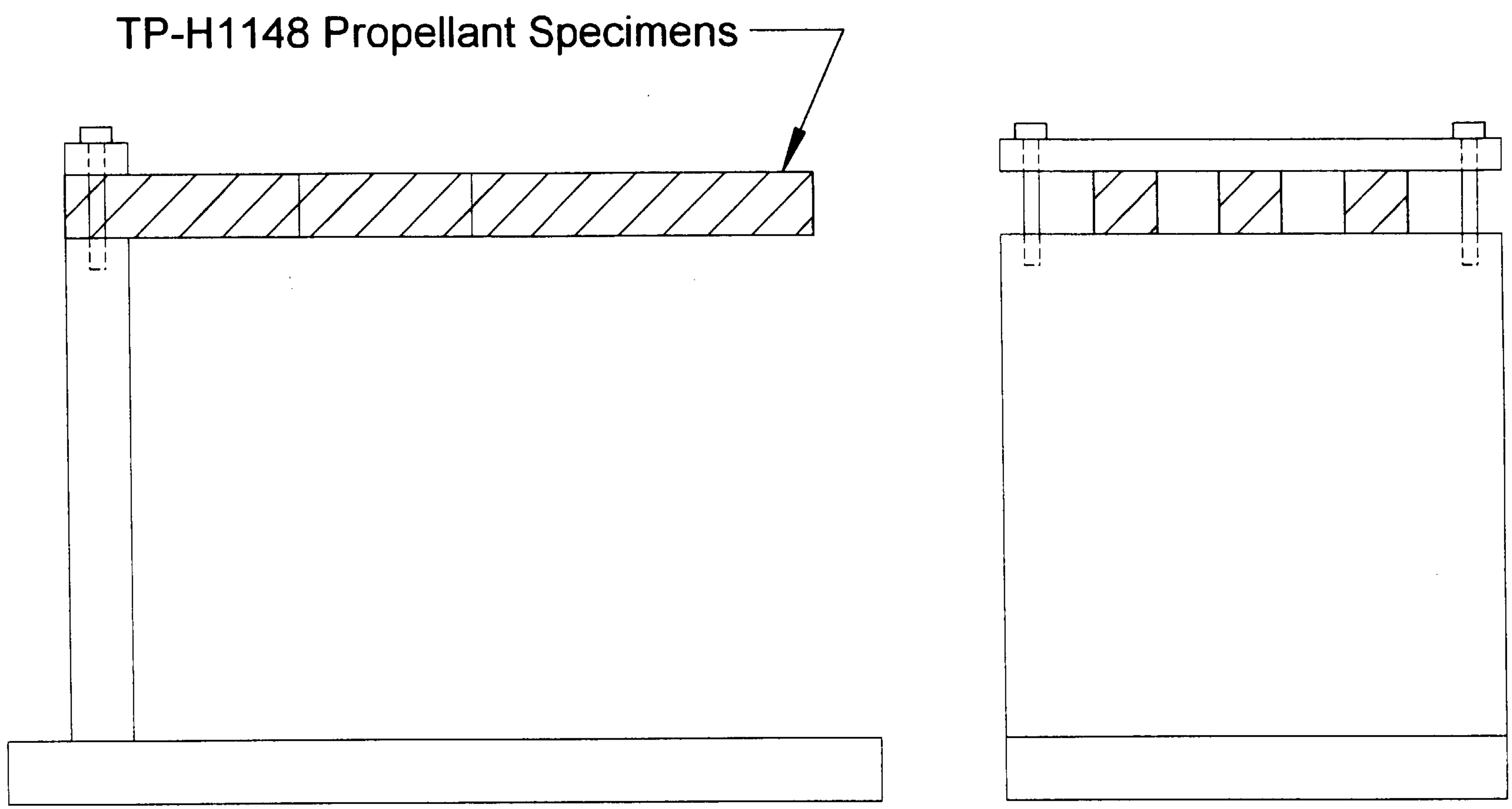

Figure 16. Cantilever Beam Test Setup

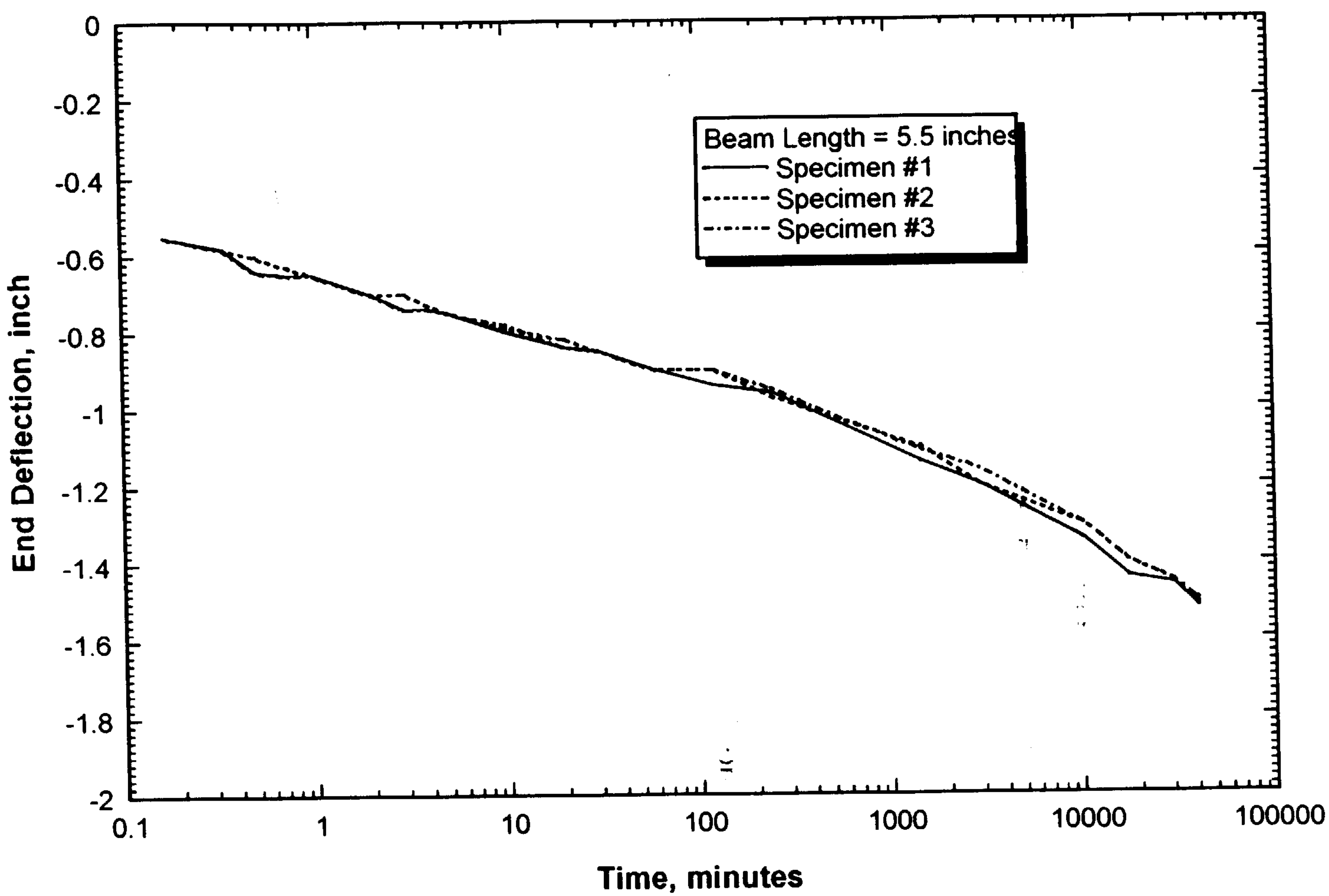

Figure 17. TP-H1148 Propellant Cantilever Beam Test, End Deflection History

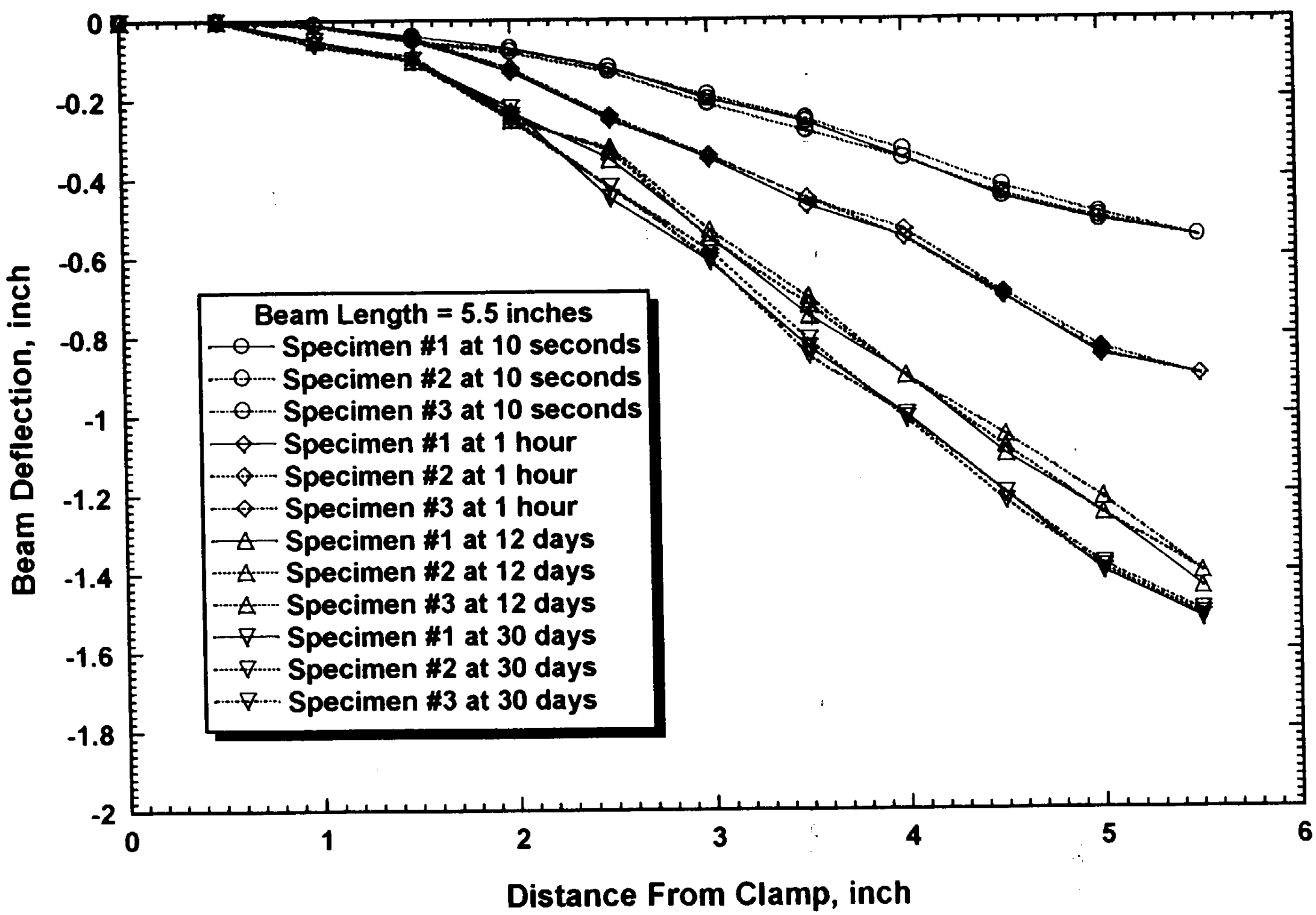

Figure 18. TP-H1148 Propellant Cantilever Beam Test, Deflection Profile

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